

# ENERGY-BASED DESIGN METHODOLOGY FOR AIR VEHICLE SYSTEMS: AERODYNAMIC CORRELATION STUDY

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## OVERVIEW

This fundamental study served to formulate and predict numerically the performance of a flexible wing in subsonic flow conditions in terms of entropy generation. The developed approach was a joint effort with AFRL personnel in energy-based design. The work represents a new and different approach for detailed drag estimation and vehicle-level utilization of energy.

The exergy utilization of a wing in a steady, low subsonic, three-dimensional, viscous flow field was modeled. This amounted to estimating the entropy generation due to the lift and the components of drag of the wing. Wing performance was evaluated for three different wing lift distributions on a rectangular, flexible wing. The power required to overcome wing drag is directly proportional to the entropy flux across the wing. In this study, methods for evaluating both the drag and the entropy flux for a wing based the predictions of a three-dimensional, turbulent computational solver were compared to estimates based on experimental airfoil data and lifting line theory predictions. Overall, we show: (1) the mapping of entropy generation clearly details regions of irreversibility in the wing flow field, and (2) under the limited conditions studied, the drag prediction obtained with a far-field entropy method developed here is improved over the traditional wing surface integration approach.

## RESEARCH OBJECTIVES

The objective of this contract was to explore and develop, in close cooperation with the Air Force Research Lab, a numerical methodology to predict the entropy production in the viscous flow fields of subsonic, small-scale flexible wings. The details of this work are available in the master thesis listed as reference [1].

## APPROACH

The steady, incompressible flow past a rectangular wing was modeled for three lift distributions for a fixed flight condition. For two distributions, the wing was geometrically twisted in order to give an elliptic and a parabolic lift distribution as prescribed by lifting line theory. The third wing geometry was untwisted but placed at an angle of attack to yield in theory the same total lift as the other two wings. All three wings were comprised of NACA 0012 airfoil sections. The wings developed are shown in Figure 1. Details of how the wings were designed and modeled can be found in reference [1]. This discussion will focus on the outcomes of this contract.

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14. ABSTRACT Estimates of the exergy utilization of a wing in a low subsonic, three-dimensional, viscous flow field were incorporated in the far-field drag calculation for three different lift distributions on a rectangular, flexible wing. The method developed here provided improved agreement between the drag and entropy values estimated numerically and the drag and entropy values predicted by empirical and lifting line methods than did using the traditional wing surface integration approach. The method also highlighted the direct link between drag and entropy production on the wing and its flow field by establishing areas of high entropy production. A method for computing entropy production within the numerical model was implemented in producing entropy contours within the flow field. Sources of drag such as the trailing wing tip vortex are clearly visible in the entropy contour figures. The ability to locate sources of drag through inspection of entropy contours in the flow field may allow the designer alter the air vehicle in a way to reduce entropy production and therefore reduce drag.					
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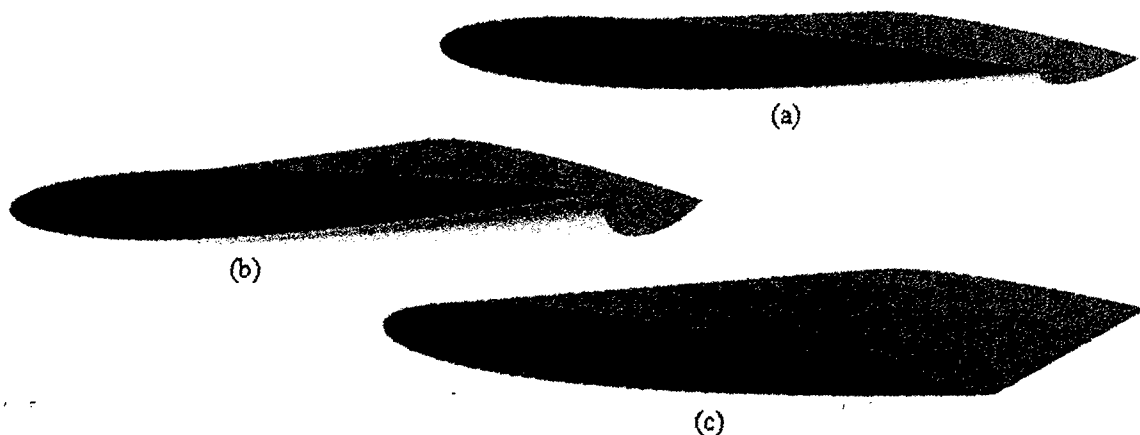


Figure 1: Wing Geometry for the (a) elliptic wing, (b) parabolic wing, and (c) untwisted wing.

For each wing, the flow field was computed by solution of the incompressible, three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations. The realizable  $k$ - $\epsilon$  turbulence model was used for closure. Two hundred points were used to define each airfoil section. The computational domain extended 5 chord lengths ahead, 20 behind, and 10 above and below the wings surfaces. Values for  $y^+$  were maintained at or below 1 at the wall. Cell growth outwards from the wing surface was limited to no more than 20% per layer. The flow field was discretized using over 4 million cells. An example is shown in Figure 2. Details on the rationale and execution of the computational grids are provided in [1].

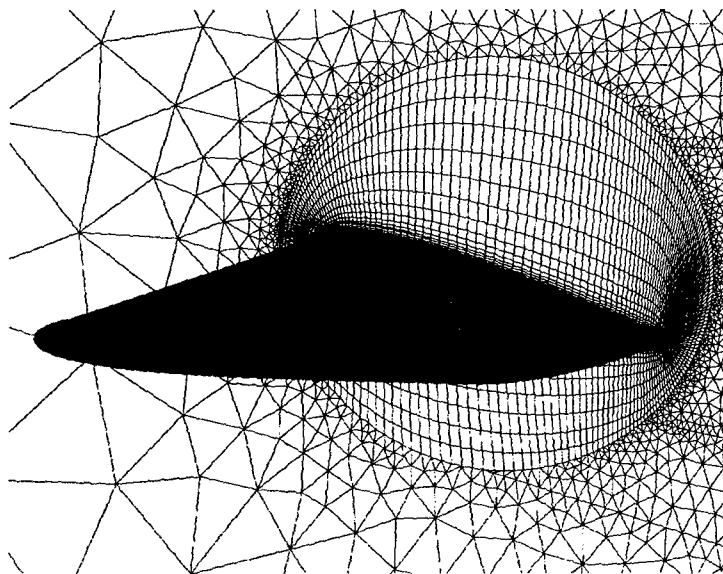


Figure 2. Twisted wing (parabolic case) and example of flow grid.

Oswatitsch [2] showed that the power required to overcome drag is directly proportional to the entropy flux across a surface enclosing all entropy changes caused by the body in subsonic, steady flow where states differ only little from the state of approach. Because the entropy changes in the flow will be due totally to the presence of the wing, the entropy flux through the surface of the control volume will be equal to the entropy generation within the control volume. Therefore, by knowing the entropy generation within a control volume that encloses all of the entropy changes caused by the wing, the drag force can be determined as

$$F_D = \frac{T_\infty}{U_\infty} \int_{CV} \dot{S}_{gen}'' dV \quad 1$$

Oswatitsch's relation between entropy and the power required to overcome drag cannot be applied directly within a numerical simulation. For example, the trailing vortex sheet may take up to 100 aircraft lengths behind the wing to be damped out [3] and such modeling may be prohibitive due to computational constraints. Hence, a numerical model would not capture all of the entropy production caused by the wing.

To meet our objective here, the extra entropy generation not accounted for in the numerical model is estimated from an exergy rate balance. This exergy rate balance is applied to a control volume placed directly downstream of the numerical model. The resulting drag relation is given as

$$F_D = \frac{1}{U_\infty} (T_\infty \int_{CV} \dot{S}_{gen}'' dV + \int_{outlet} \rho u_2 \frac{v_2^2 + w_2^2 + (U_\infty^2 - u_2^2)}{2} dA) \quad 2$$

where  $U_\infty$  and  $T_\infty$  are the approach velocity and temperature, respectively. The three velocity components  $u_2$ ,  $v_2$ , and  $w_2$  are the x, y, and z velocity components of the fluid leaving the numerical model. The x coordinate represents the streamwise direction, the y coordinate represents the vertical direction, and the z coordinate represents the spanwise direction. The value  $\dot{S}_{gen}''$  is the local entropy production rate. For flows without heat transfer,  $\dot{S}_{gen}''$  is equal to the product of the viscous dissipation function and the fluid viscosity divided by the fluid temperature [4].

## RESULTS

Results were obtained for each wing geometry based on the following conditions: wing weight = 7300 N, rectangular planform with no aerodynamic twist with AR = 6, c = 1 m; flight conditions: M = 0.2 under steady (static flight) conditions.

The comparison between the intended, theoretical lift distributions and the computationally achieved quarter-chord lift distributions are shown in Figures 3, 4, and 5. The comparisons are quite good across the span. Minor deviations are seen to occur near

the wing tip as a result of the high lift gradients that occur there. The integrated lift under each distribution is consistent between each case to within 1%.

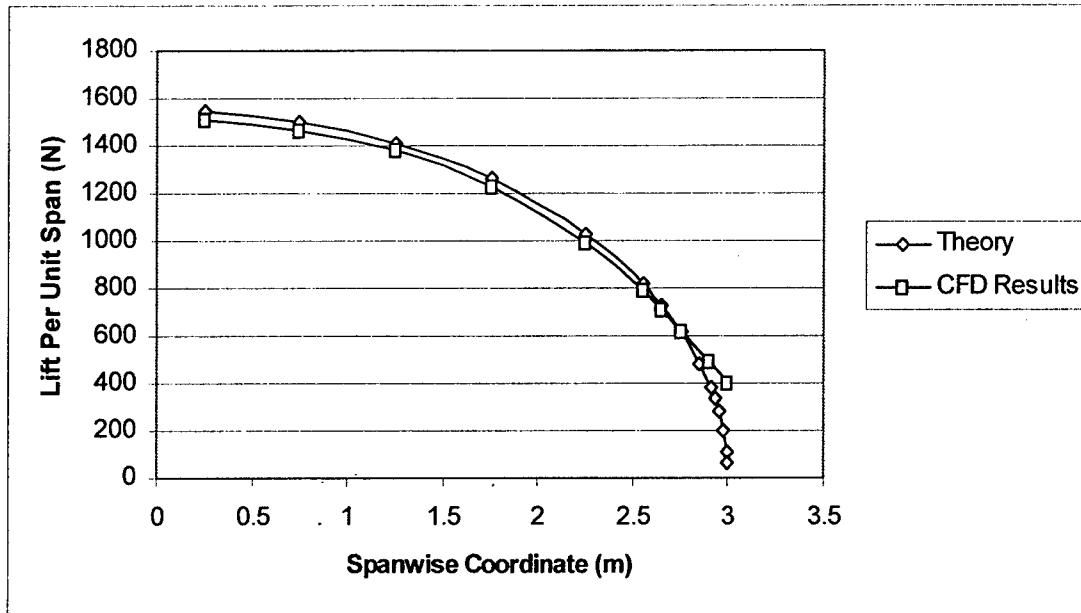


Figure 3: Spanwise Lift Distribution for Elliptic wing Compared With Actual Elliptic Lift Distribution

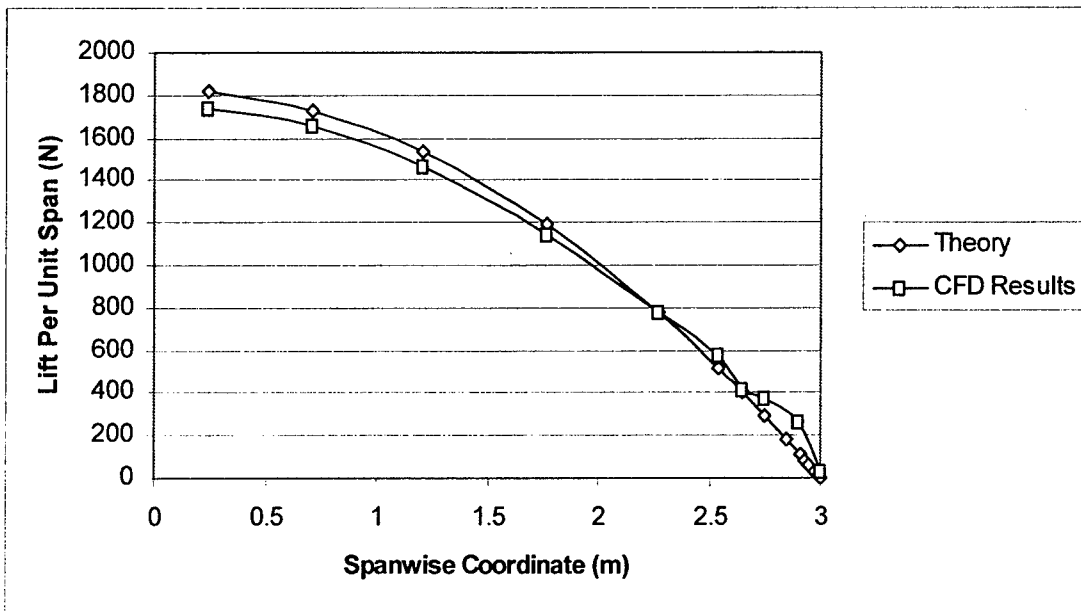


Figure 4: Spanwise Lift Distribution for Parabolic Wing Compared with Actual Parabolic Lift Distribution

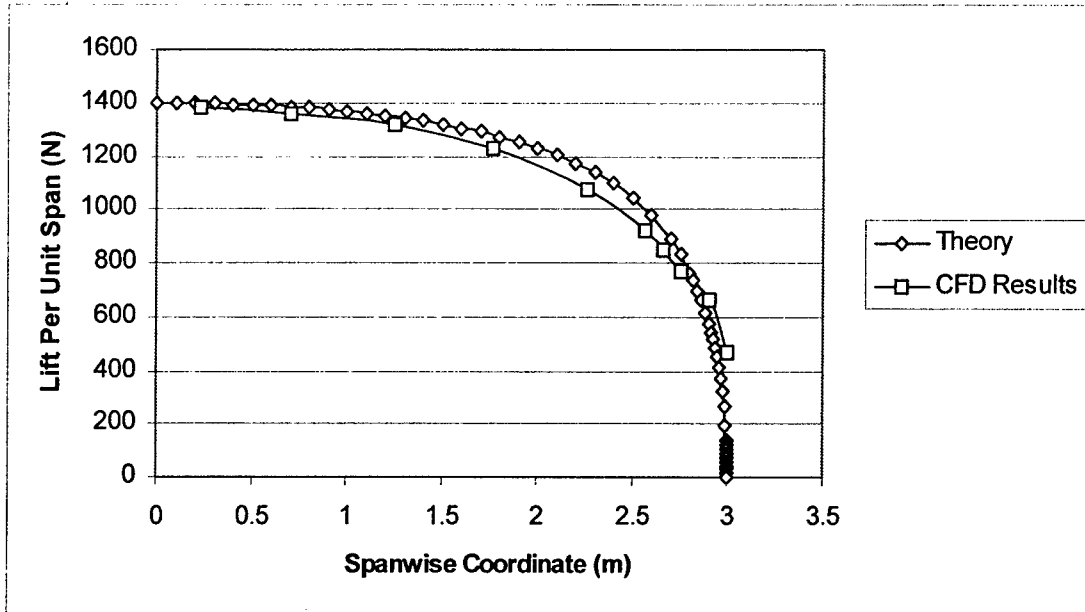


Figure 5: Spanwise Lift Distribution for Untwisted Wing Compared with Theoretical Untwisted Lift Distribution

The approach represented by Equation 2 was applied separately to eight different volumes, each extending from one chord length to eight chord lengths downstream of the wing with results shown in Figure 6. The total drag coefficient retains a nearly constant trend as the numerical volume extends further downstream of the wing. For example the drag coefficient taken at one and eight chord length downstream of the wing are within 0.02%, 0.98%, and 0.31% of each other for the elliptic, parabolic, and untwisted wing respectively.

For validation purposes, a semi-empirical drag value was constructed as the additive combination of two drag components: (1) the well-documented two-dimensional NACA 0012 airfoil experimental data [5], and (2) the induced drag for these wings as predicted by Prandtl's lifting line theory. The average drag value obtained with the far-field method agreed with the semi-empirical drag result to within 3.4%, 2.6%, and 4.4% for the elliptic, parabolic, and untwisted wing respectively.

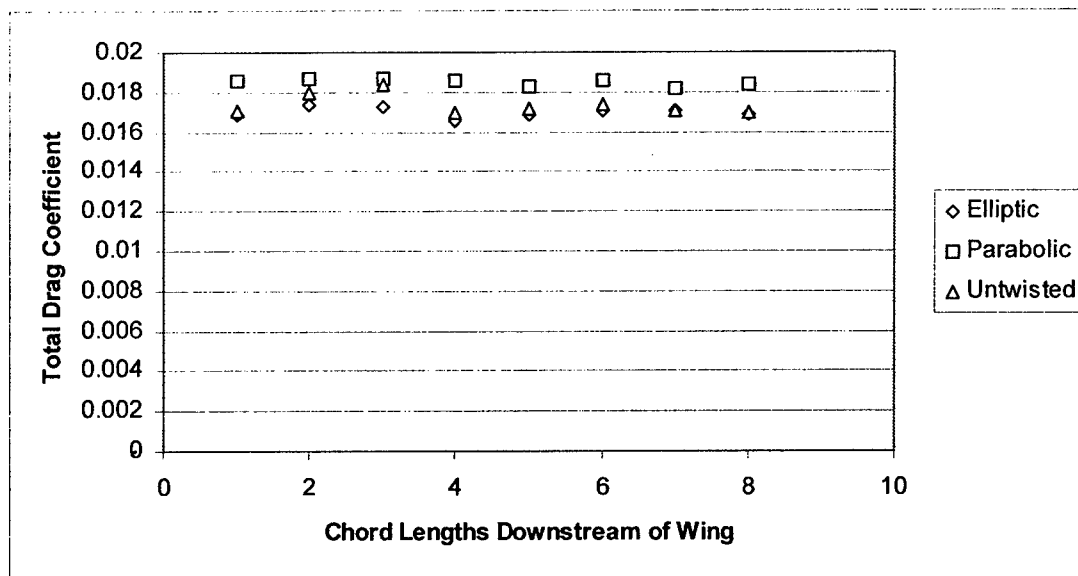


Figure 6: Total Drag Coefficient Determined as the Numerical Volume Extends Further Downstream of Wing

To avoid effects from numerical dissipation in the downstream wake region and to avoid large changes from the freestream in the immediate region directly behind the wing that could exacerbate any errors in the numerical model, it may be appropriate to use the drag values taken at an intermediate downstream position. For example, the drag value determined using Equation 2 at two chord lengths downstream of each wing was within 1.1%, 1.6%, and 1.1% to the semi-empirical value for the elliptic, parabolic, and untwisted wing respectively. As a comparison, the drag value obtained through conventional wing surface integration was off from the semi-empirical value by 12.5%, 13.2%, and 8.8% for the elliptic, parabolic, and untwisted wing, respectively.

The results show that the elliptic wing has the lowest total drag with the parabolic wing having the highest value. Interestingly, Greene [6] used Oswatitsch's relation between drag and entropy in an effort to optimize the wing circulation distribution to minimize induced drag. His findings, which included efforts to minimize bending moment, suggested that the optimum distribution is parabolic; a result in disagreement with lifting line theory that gives an elliptic distribution as optimum. Although this study is focused on total drag rather than induced drag, full field entropy production was found to be at a minimum with the elliptic wing, which remains consistent with lifting line theory versus Greene's findings.

The far-field method developed offers the potential for better drag prediction as compared to the wing surface integration technique with a conventional solver. The method also clearly demonstrates the direct relation between drag and entropy production, which itself is directly proportional to exergy destruction. The volume integration for determining entropy production can be used to produce entropy contours within the numerical model to locate sources of drag. This is illustrated in Figures 6, 7,

and 8, which detail entropy production at the root plane and at several indicated planes (Trefftz planes) downstream of the elliptic, parabolic, and untwisted wing, respectively. The trailing wing tip vortex for the elliptic and untwisted wing is clearly defined by the entropy production caused by the shearing action of the vortex. The intensity of the entropy production diminishes within the core of the vortex as the vortex is convected downstream. The trailing vortex sheet is responsible for increasing drag on a wing as compared to its two-dimensional counterpart. Entropy production is also predicted at each location on the wing surface, with the highest production along the leading edge. By plotting entropy contours within the numerical model, and considering Equation 1, the relation between drag and the trailing vortex is made clear.

Existing models, including lifting line theory and panel methods, do relate the trailing vortex sheet in terms of the induced drag on wings but they do this in a global sense. Euler codes account only for the induced drag. The method developed here clearly identifies the sources of viscous and induced drag on complete air vehicle assemblies; traditional analytical techniques offer far less detail. Under the flight conditions here, any reductions in entropy production caused by the wing will ultimately reduce drag. Clearly, the prediction of drag will be affected by the turbulence model used, particularly at these flow conditions. The effect was not studied here within the timeframe of the contract

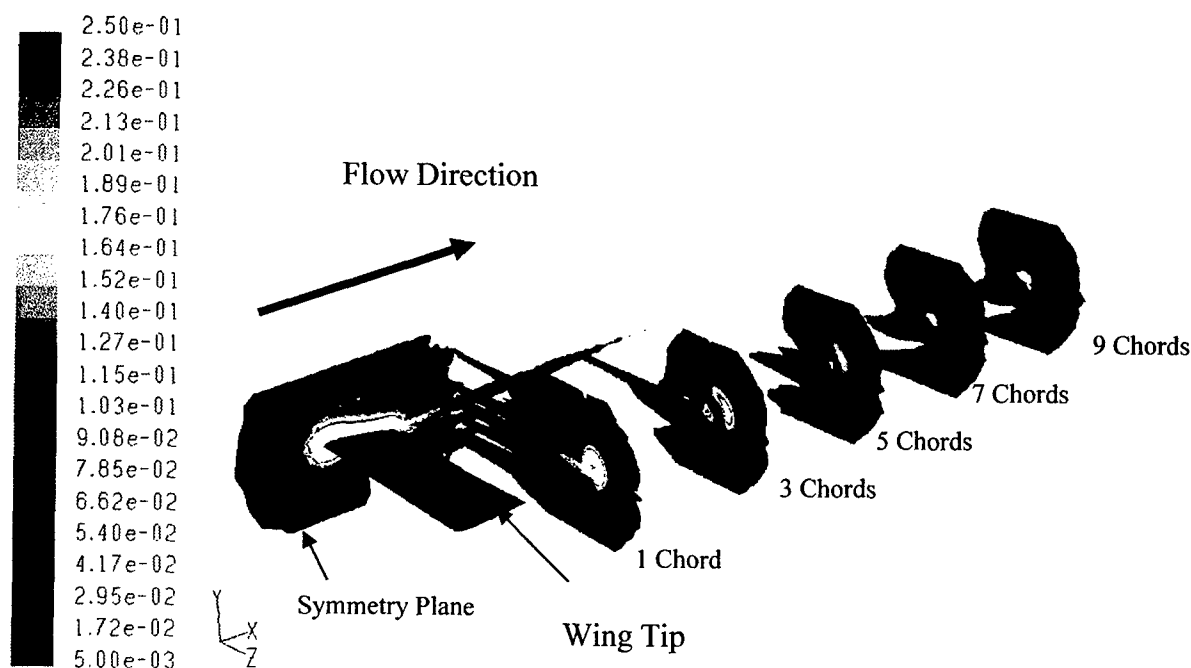


Figure 6: Entropy ( $W/(m^3 K)$ ) Contours on Symmetry Plane and on Various Trefftz Planes at the Indicated Distance Downstream of the Elliptic Wing.



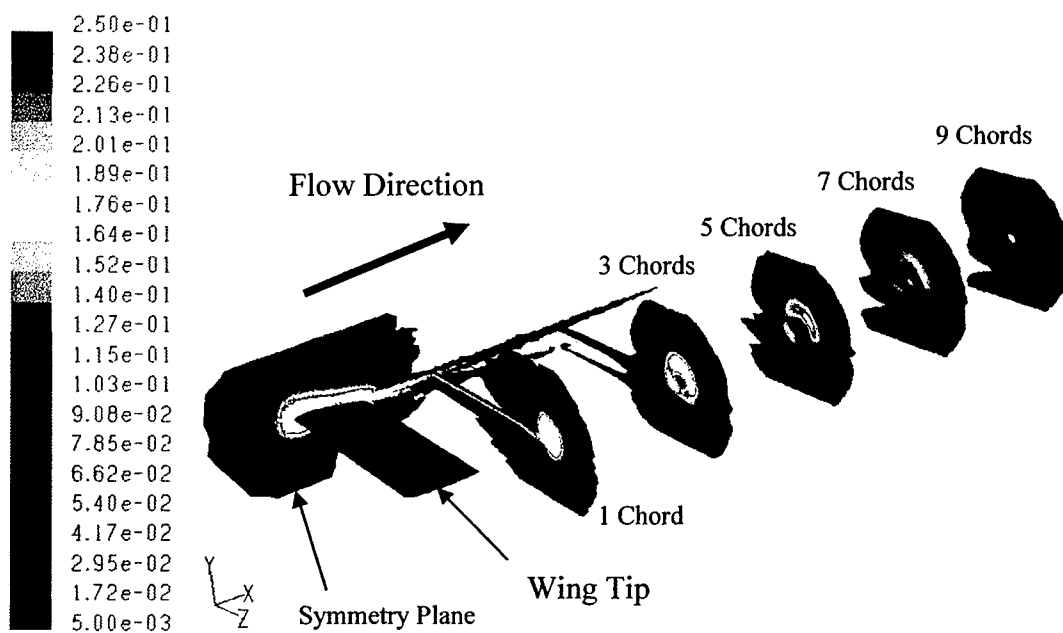


Figure 7: Entropy (W/(m<sup>3</sup> K)) Contours on Symmetry Plane and on Various Trefftz Planes at the Indicated Distance Downstream of the Untwisted Wing.

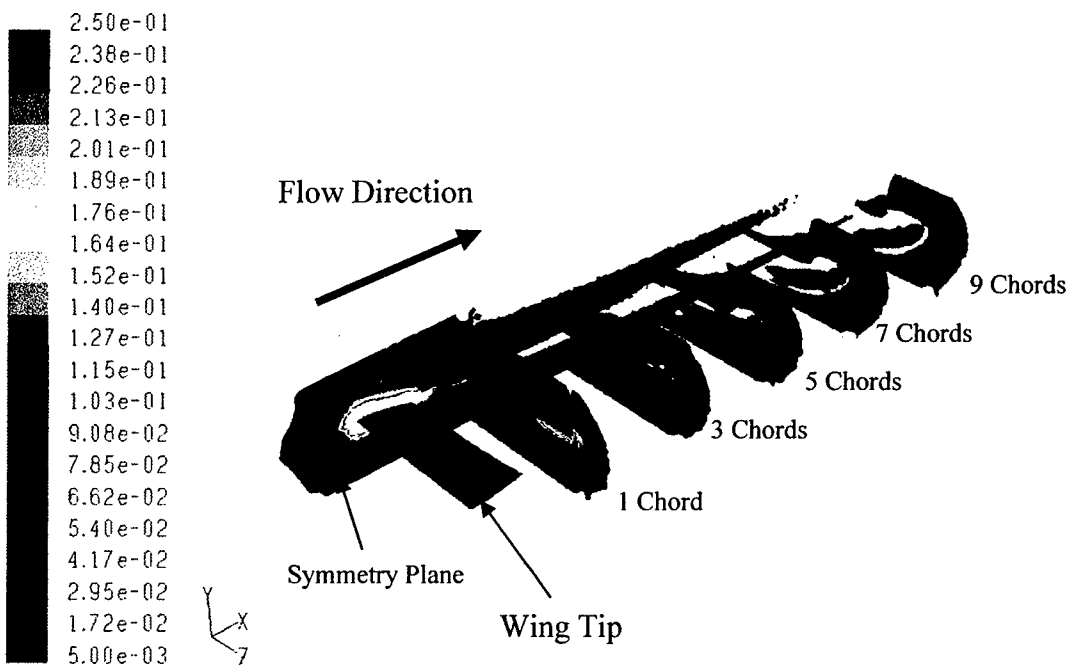


Figure 8: Entropy (W/(m<sup>3</sup> K)) Contours on Symmetry Plane and on Various Trefftz Planes at the Indicated Distance Downstream of the Parabolic Wing.

## CONCLUSION

Estimates of the exergy utilization of a wing in a low subsonic, three-dimensional, viscous flow field were evaluated using a far-field drag calculation of three different wing lift distributions on a rectangular, flexible wing. Not only did the method developed here provide improved agreement between the drag and entropy values predicted numerically and the drag values predicted empirically and by lifting line methods than did using the traditional wing surface integration approach, but it highlighted the direct link between drag and entropy production on the wing and its flow field. A method for computing entropy production within the numerical model was implemented in producing entropy contours within the flow field. Sources of drag such as the trailing wing tip vortex are clearly visible in the entropy contour figures. The ability to locate sources of drag through inspection of entropy contours in the flow field may allow the designer alter the air vehicle in a way to reduce entropy production and therefore reduce drag. More successfully, a method for computing the entropy production in a flow field was developed that may lead to improved wing shapes based on a vehicle-level energy audit.

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6. Greene, G., 1989, "An Entropy Method For Induced Drag Minimization," SAE Technical Paper Series, No. 89-2344.

## **Personnel Supported**

- a. Faculty  
Richard Figliola, Professor, Clemson University
- b. Graduate Students  
Jason Stewart, MS degree, May 2005, Clemson University

## **Publication**

Li H., Figliola R., Stewart J., "Exergy Based Design Methodology for Airfoil Shape Optimization," Proc. AIAA MAO Conference, September 2004.

Stewart J., Li H., Nomura S., Figliola R., Camberos J., "A far-field method for estimating both the exergy utilization and the drag of a wing in a subsonic, viscous flow," in preparation, AIAA J Aircraft, 2005.

Stewart J., An Exergy-Based Study of Three-Dimensional Viscous Flow Over Wings, MS Thesis, Clemson University, April 2005.

## **Interactions/Transitions**

- a. Participation

Figliola, R., Stewart, J., and Nomura, S., Exergy Study for Aircraft Systems Integration: Entropy Estimation, VASD Symposium, AFRL, August 2004.

Figliola, R. "Exergy Based Design Methodology for Airfoil Shape Optimization," AIAA MAO Conference, September 2004. with H. Li (Clemson graduate student)

- b. Consultative/Advisory Functions

Second law analysis team member, Air Force Research Laboratory, VASD/VAAC, May 17 – July 30, 2004. PI spent three weeks at AFRL interacting with AFRL staff and students. AFRL staff involved: D. Moorhouse, J. Camberos, D. Jackson.

- c. Transitions

Validation of entropy calculations in Cobalt-60/AVUS and suggested changes to code for broader applicability to wing/vehicle design. AFRL. Dr. Jose Camberos.

## **New Discoveries/Inventions/Patents**

None.

## **Honors/Awards**

None.